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Field and Laboratory Evaluation of a Woodstove Dilution Sampling System

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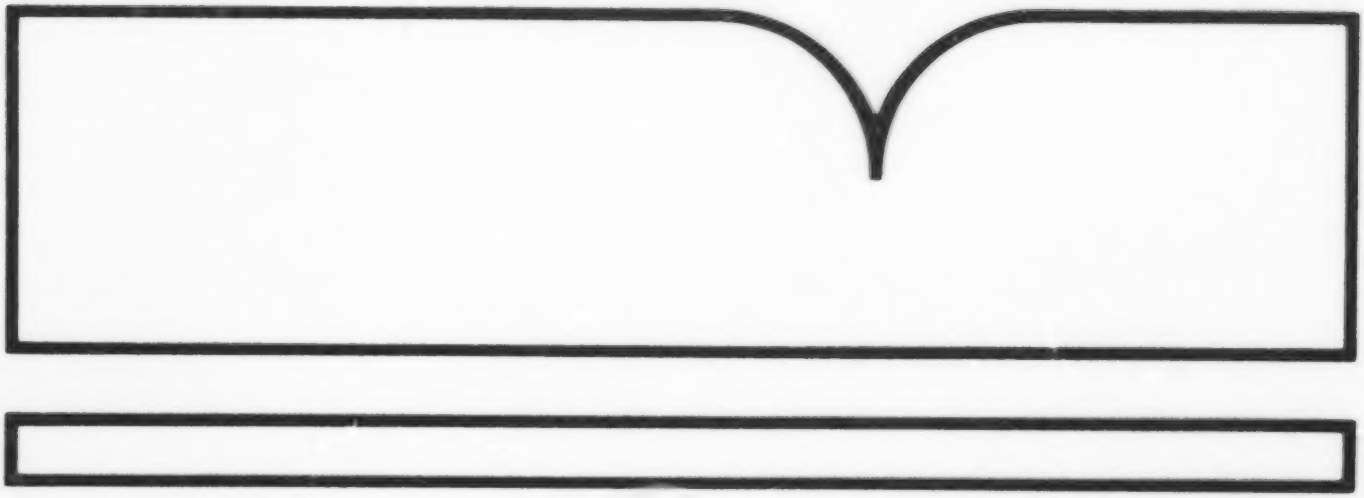

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16. ABSTRACT The paper discusses field and laboratory evaluation of a woodstove dilution sampling system. Two sampling methods have been developed and used by EPA to test emissions from woodstoves: both remove flue gas directly from the appliance chimney. The two methods have been developed to meet two goals of EPA sponsored research and development: (1) the woodstove dilution sampling system (WSDSS) addresses the need to simulate or model the atmosphere/stack interface and to provide emissions samples as they are distributed between vapor phase and particle bound material; and (2) the modified method 5 (MM5) system addresses the need to perform direct source sampling without dilution or condensation. MM5 samples correspond more to materials as they are found in the flue gas stream where emission controls would be applied. The WSDSS has recently been used in a major field study. The MM5 and WSDSS methods have also been compared in simultaneous woodsmoke tests. Results from field use of the WSDSS are discussed. Comparison of the WSDSS and MM5 sampling systems in laboratory tests is presented.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Flue Gases	Stationary Sources	13A
Stoves	Woodstoves	11L
Tests		21B
Wood		14B
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Sampling		
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ABSTRACT

Two sampling methods have been developed and used by EPA to test emissions from woodstoves. Both methods remove flue gas directly from the appliance chimney. These two methods have been developed to meet the two goals of EPA sponsored research and development. The woodstove dilution sampling system (WSDSS) addresses the need to simulate or model the atmosphere/stack interface and to provide emissions samples as they are distributed between vapor phase and particle bound material. The modified method 5 sampling system (MM5) addresses the need to perform direct source sampling without dilution or condensation. MM5 samples correspond more to materials as they are found in the flue gas stream where emission controls would be applied. The WSDSS has recently been used in a major field study. The MM5 and WSDSS methods have also been compared in simultaneous woodsmoke tests.

Results from field use of the WSDSS are discussed. Comparison of the WSDSS and MM5 sampling systems in laboratory tests is presented.

INTRODUCTION

Woodstove emissions testing is currently of national interest. Two approaches have been taken by EPA R&D to test emissions from woodstoves to meet two quite different goals. Two sampling systems have been developed for collection of a wide range of organic emissions to meet the goals of the two approaches. Measurement of the distribution of material between that which is volatile and that which is condensed or particle bound is the distinguishing feature of the two methods. The method which measures the distribution as it is found in the flue or exhaust ductwork is modified method 5 (MM5). EPA has developed sampling systems such as the MM5 train and successfully applied them to industrial sources(1). Research programs to define the impact of residential wood combustion have also used the MM5 system (2,3). The MM5 sampling system addresses the need to perform direct source sampling without dilution or condensation. The distribution of samples within the MM5 train corresponds more to materials as they are found in the flue gas stream.

The surge of interest in residential wood combustion appliances has added a non-industrial source which requires the ability to distinguish between vapor phase and particulate organic material after they are cooled and diluted in the ambient air near the flue or stack. Measurement which addresses the distribution as it is found in the ambient air presents formidable problems for conventional stack sampling methods. A dilution sampler designed to collect cooled particulate from industrial sources has been developed (4). The design concepts for the industrial source dilution sampler have been applied to residential wood combustion

source sampling. The resulting Woodstove Dilution Sampling System (WSDSS) addresses the need to simulate or model changes that occur in emissions at the atmosphere/stack interface and to provide emissions samples which relate to vapor phase versus particle bound material under near-source ambient temperature conditions. The results of a comparison of the WSDSS and the MM5 system are described in this paper.

Woodstove Dilution Sampling System

During the past several years EPA has been involved with the development and testing of sampling trains for condensible emissions. A Woodstove Dilution Sampling System (WSDSS) based on a scaled down version of a sampling train used to measure inhalable particulate from stationary sources of air pollution has been designed, constructed, and tested. The WSDSS was designed to be mechanically suitable for *in situ* residential wood combustion emissions measurement. The WSDSS uses dilution of a sample extracted from the stack to perform this simulation. After dilution, particulate and condensed material is collected on a fiberglass or Teflon-coated fiberglass filter. A porous polymer adsorbent module follows the filter to collect semivolatile organic material passing through the filter. A diagram of the major components of the WSDSS is shown in Figure 1. The unit sits atop the exit of the chimney on a plate that is in a position typical of chimney rain shields.

In operation, sample gas is extracted from the chimney flue through a sharp-edged nozzle, heated probe, and inlet section. The sample is introduced axially into the bottom of the cylindrical dilution chamber. The dilution air enters the sample inlet section perpendicular to the sample flow as shown in Figure 2. The dilution air is then deflected toward the bottom of the inlet section to aid in providing an even flow distribution throughout the annulus. Before mixing with the sample gas, the dilution air travels up through a region containing approximately 2250 flow straightening glass capillary tubes (1.8 mm O.D. x 1.5 mm I.D. x 100 mm long). At this point the stack gas joins dilution air to form a simulated plume which flows up through the 1.2 m (4 ft) long x 10.2 cm (4 in.) I.D. dilution chamber. The laminar annulus of dilution air ensures that mixing does not occur too quickly, simulating buoyant plume injection into stagnant air. Laboratory tests show that the sample has spread across the tube and cooled to near ambient temperature by the time it has traveled 75% of the tube length.

After the sample gas and dilution air have mixed, the mixture passes into the filter/sorbent housing shown in Figure 3. Particulate matter produced by direct combustion, along with any new particulate formed by condensation, is collected on a 142 mm filter. Organic substances which remain in the vapor phase or which are lost from the filter by revaporization are adsorbed by an XAD-2 resin cartridge in series downstream from the collection filter. The exhaust gas then exits the housing to the control module and a 0.28 cubic m^3/min (10 cfm) exhaust pump.

Gas flows in the WSDSS are controlled from the ground using a differential pressure cell to monitor probe flow through a venturi and dilution flow through an orifice both prior to the dilution chamber. The WSDSS does not precondition-condition dilution air beyond particulate filtration because the current test objectives require dilution with air at ambient conditions. Diluting with ambient-condition air will ensure that the plume

simulated inside the dilution chamber most nearly represents actual, local plume formation. Dilutions are typically on the order of 20/1 with a possible range of 5/1 to 40/1.

The geometric and flow specifications of the WSDSS (Table 1) have been set by several constraints and represent a compromise dictated by limitations on the size of a portable field instrument to be used on residential chimneys.

Modified Method 5 (MM5) Train

The purpose of this sampling system is to measure all extractable organic material (EOM) from flue emissions. The sampling system design of the MM5 is adapted from units that are typically used for EPA Method 5 sampling (5). The modification to the Method 5 system includes the addition of a sorbent module, containing a porous polymer resin (XAD-2) designed to efficiently trap vapor-phase organic compounds with vapor pressures less than that of heptane (boiling points nominally greater than 100°C). The MM5 train typically samples 3 dscm (100 dscf) during a 4 hour sampling period, operating at a flow rate of 0.015 dscm (0.5 dscfm). Operating time can be increased by replacing filters as they are plugged and/or by increasing the quantity of sorbent resin.

Operation of the MM5 train involves removing gaseous and particulate emissions from the flue gas source. Isokinetic sampling rates are required for sources containing particles larger than 1 um. Proportional sampling may be used when particles are smaller than 1 um. The principal components of the train shown in Figure 4 include a probe constructed of inert material, a high efficiency heated glass or quartz fiber filter, a cooled packed bed of porous polymer adsorbent resin (shown in Figure 5), and a set of impingers (empty, filled with water, and filled with silica gel, respectively).

The use of the MM5 train as a comprehensive organic sampling system has been increasing because of its inert construction and adaptability to many different stationary sources of pollution. All surfaces that contact the sample, except the probe tip, are glass, Teflon, or other inert material. The major advantage of this system is that particulate loading concentration data can be obtained according to EPA Method 5 while a representative sample of organic material is collected on which quantitative analysis of total organic material and specific organic compounds can be made.

Analysis

Three discrete samples for chemical analysis are recovered from the WSDSS and the MM5 sampling systems. One sample comes from the probe wash, filter housing wash, and connecting tubing (including the dilution tube in the WSDSS). The second sample comes from processing the filter. The third sample comes from the XAD-2 sorbent and sorbent module wash. An additional sample can be collected from the MM5 train, including the condensate and condensate impinger wash. For results reported here, rinses were performed with both dichloromethane and methanol.

Extracts of the collected samples are chemically analyzed to determine the extractable organic matter (EOM). Analyses were performed separately on the methanol and dichloromethane extracts of sampling train components. A gravimetric (GRAV) determination of an aliquot of the concentrated soxhlet extract of each

sample or wash is used to quantify organic material that has a vapor pressure less than that of hexadecane (bp. 298°C). A gas chromatographic analysis (TCO) is performed on an aliquot of appropriate samples to determine the amount of organic material with vapor pressures in the range of those for heptane to hexadecane (bp.98 to 298°C). The sum of TCO and GRAV is EOM. The extracted samples may be comprehensively analyzed to identify and quantify specific organic material (5,6).

Results

Field Data

The four residential wood combustion appliances tested in the field were conventional, non-catalytic units that had been used by homeowners as primary heating systems. Each stove was operated by the respective homeowner as it normally would. The data collected are summarized in Table 2. The mass measured using the dilution system was dominated by particulate and condensed organic material for the stoves under the ambient temperature and dilution conditions existing during the sampling periods. The mass measured varied considerably between runs on the same stove and among the four stoves. This is due to source variability rather than sampling error since other samplers have shown the same trend (3). The quantity and phase distribution of EOM from wood combustion depends on the woodstove design and operation and sample collection temperature.

The sampling period from 7 pm to 7 am was chosen because it included the time of stable air conditions in the test area and therefore the time the stoves would have their biggest effect on the ambient air. The original goal of one continuous sampling period was not met for these tests due to increases in pressure drop across the filter. Ambient temperatures (and dilution air) remained near 0°C for the entire field test period. With experience, the minimum time to change the filter has been decreased to 10 minutes. No attempt was made to control the sample flow at isokinetic condition because no field usable technique was available to measure the low velocity found in the chimneys. A constant 5.7 lpm (0.2 scfm) flow was withdrawn from the flue by the sampling system during normal evening stove operation, and this flow was reduced to 2.9 lpm (0.1 scfm) when the stove was banked for the night with a full charge of wood and the draft settings decreased to a minimum by the homeowner.

Heavy loading of the filter was experienced during these tests with as many as three filter changes needed during each 12 hour sampling period. Data for these tests are summarized in Tables 2 and 3. The material recovered from the probe and dilution tunnel portion of the woodstove dilution sampling train was always less than 10%. This material is captured before the filter by either diffusional loss or because the material particles are larger than 10 um. The amount of material retained by the filter was approximately 75% of the total mass collected, and the percentage depended on the dilution air temperature. Approximately 25% of the stove organic emissions collected by the WSDSS passed through the filter and were captured from the vapor phase onto the sorbent resin.

Laboratory Comparison of MM5 and WSDSS

The WSDSS was operated on a laboratory woodstove test stand simultaneously with a Modified Method 5 stack sampling train. The primary goal of the laboratory study sampler comparison was to evaluate the WSDSS and MM5 sampling systems operating simultaneously. The comparisons used pine and oak fuel under different firing and moisture conditions. The comparison of emission rates from oak and pine under a variety of conditions has been reported elsewhere (7).

Tests were run in the late spring with ambient temperatures reaching 30 to 40°C. During the test sequence the MM5 filter plugged on several occasions, and continuous sampling was not possible. The WSDSS was operated continuously over the entire 6 to 8 hour burn period, covering several wood additions. All tests started with a hot stove.

The comparison of organic emissions collected by the sampling trains is shown in Table 4. The net weights of material caught on the WSDSS filters for these sampling runs ranged between 0.1 and 0.8 g. Organic analysis for EOM on the samples is given in Tables 4 and 5. In all cases the WSDSS was within 30% of the MM5 emission results, and on the average was approximately 20% higher than the MM5 results. More than 60% of the organic emissions collected by the WSDSS were on the XAD-2.

Discussion

The difference in mass distribution (Figure 6) between WSDSS field and laboratory data is a clear indication of the effect of ambient dilution air temperature. The larger percentage of sample collected on the XAD-2 with elevated ambient temperatures demonstrates the need for a collector media following the particulate filter in the WSDSS.

The percentage of material which passes through the filter in the WSDSS depends on the dilution air temperature, thus modeling what may occur with emissions immediately after release into the environment. The percent filter collection of the particle-bound material can vary with the source; however, the total percent particle-bound material from the probe and dilution tunnel remains relatively small compared to filter and sorbent collection. The distribution of material between filter and sorbent depends on dilution temperatures and on many other factors including stove design, burn rate, and fuel.

There can be several explanations for the approximately 20% loss of mass collected by the MM5 compared to the WSDSS in the laboratory studies. One cause could be degradation of the semivolatile material through a process like pyrolysis in the heated probe of the MM5 train. Another may be the use of filtered ambient dilution air in the WSDSS. Still another may be a bias between the two laboratories performing the EOM analysis of MM5 or WSDSS samples.

Conclusions

A dilution sampling system has been successfully applied to residential wood combustion appliances. The data from a laboratory comparison of the dilution sampler and a modified method 5 stack sampling system show good agreement.

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Evaluation of the distribution of PAH materials between particulate and vapor phase is underway.

Future Activity with the WSDSS

A new project is nearing completion to develop a field acceptable low velocity sensor. Successful development of this device would allow isokinetic samples and, therefore, emission factors to be determined for residential wood combustion sources. The prototype WSDSS has provided stable flow control for sampling which could be automated. When combined with a velocity sensor, an automatic, isokinetic sampler is possible. Many manual control items in the prototype sampler could be replaced with a microprocessor system, and this automated control would drastically reduce the size of the control box. A larger filter (8x10 in.) has also been demonstrated which should eliminate filter changes. When all of these items are combined, a remotely actuated automatic isokinetic dilution sampling system for woodstoves and other low velocity combustion units is possible.

End Notes

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Table 1.

SPECIFICATIONS FOR WOODSTOVE DILUTION SAMPLING SYSTEM

Geometric	
Active Length of Dilution Chamber	103.2 cm (40.65 in.)
Diameter of Dilution Chamber	9.83 cm (3.87 in.)
Diameter of Sample Inlet Tube	7,831 cm (477.8 in.)
Flow (Nominal)	
Sample Flow	7.08 l/min (0.25 scfm)
Sample Velocity (143°C)	40.5 cm/sec)(15.9 in./sec)
Dilution Air Flow (51°C)	25.6 cm/sec (10.1 in./sec)
Dilution Ratio	16.1
Residence Time	4.2 sec
Gas Conditions	
Sample Gas:	109°C < T < 198°C
Dilution Air:	Filtered, ambient air
Sample Collection	
Particulate Collection	142 mm filter
Organic Vapor Collection	resin cartridge (200 g XAD-2)

Table 2.

SUMMARY FOR WSDSS FIELD STUDIES
(g/scm)

Home No.	Probe	Filter	XAD-2	Total
1	0.08	0.69	0.28	1.05
	0.02	1.62	0.63	2.27
2	0.03	0.21	0.23	0.47
	0.01	0.78	0.22	1.01
3	0.01	1.03	0.13	1.17
	0.09	1.20	0.41	1.70

Table 3.

SUMMARY FOR WSDSS FIELD STUDIES
(EOM by volatility in g/scm)

Home No.	TCO	GRAV	Total
1	0.27	0.78	1.05
	0.52	1.75	2.27
2	0.17	0.31	0.48
	0.23	0.78	1.01
3	0.07	1.10	1.17
	0.31	1.39	1.70

Table 4

WSDSS AND MM5 LABORATORY STUDIES
Semivolatile & Condensible
(g/scm)

Burn Rate	Sampler	TCO	GRAV	Total
Low	WSDSS	1.54	2.69	4.23
	MM5	0.62	2.24	2.86
Low	WSDSS	1.56	3.04	4.60
	MM5	0.93	2.79	3.72
High	WSDSS	0.03	0.05	0.08
	MM5	0.03	0.06	0.09
High	WSDSS	0.59	0.67	1.26
	MM5	0.16	0.48	0.64

Table 5.

WSDSS AND MM5 LABORATORY STUDIES
Mass by Train Component
(g/scm)

Burn Rate	Sampler	Probe	Filter	XAD-2	Total
Low	WSDSS	0.16	1.80	2.27	4.23
	MM5*				2.85
Low	WSDSS	0.18	2.73	1.69	4.60
	MM5				3.72
High	WSDSS	0.02	0.01	0.05	0.08
	MM5				0.09
High	WSDSS	0.08	0.38	0.80	1.26
	MM5				0.65

* MM5 probe, filter, and XAD-2 data not available separately

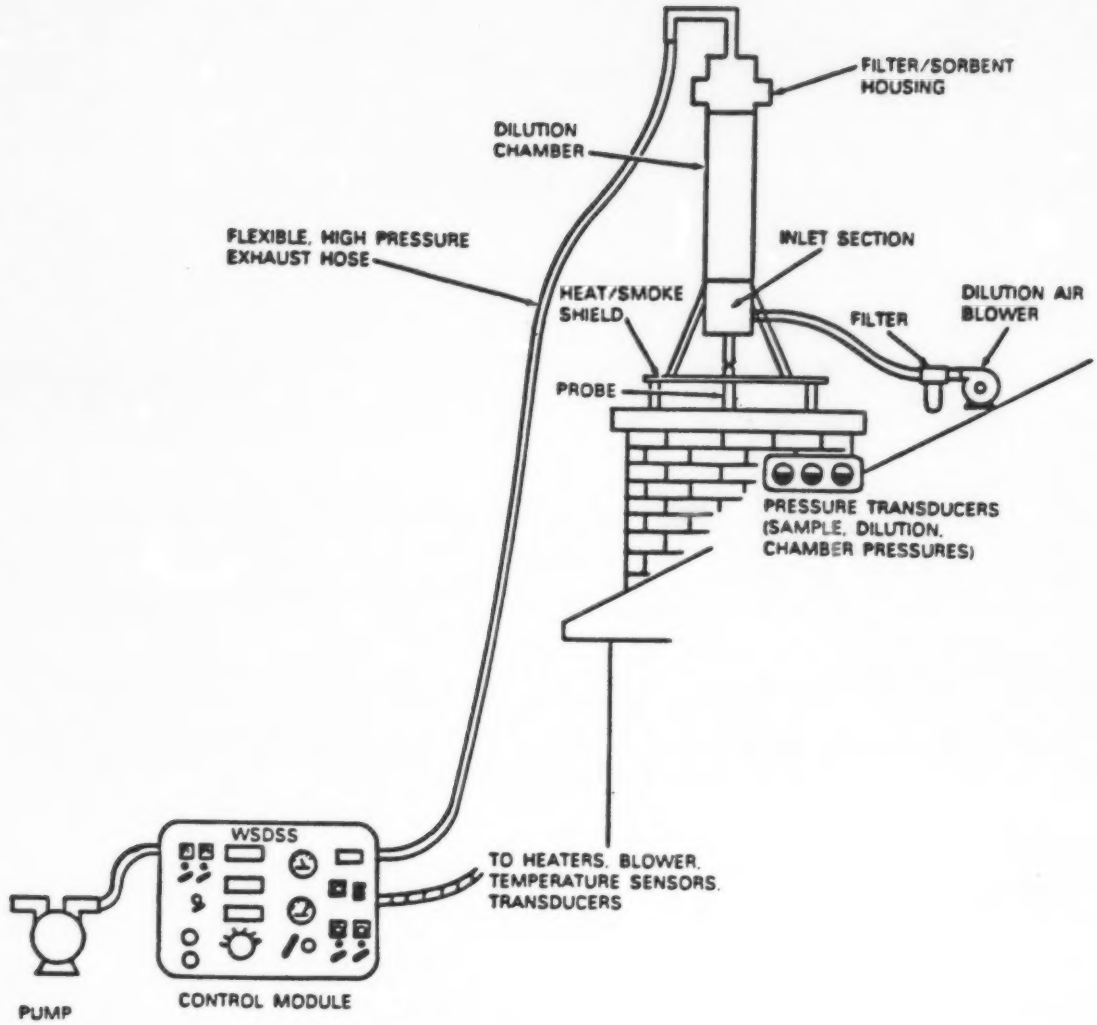

Figure 1. Diagram of the woodstove dilution sampling system.

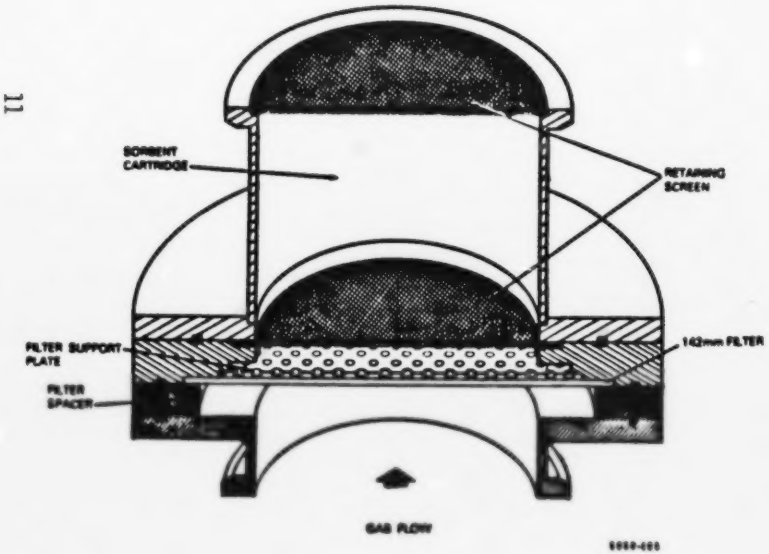

Figure 3. Filter/sorbent housing.

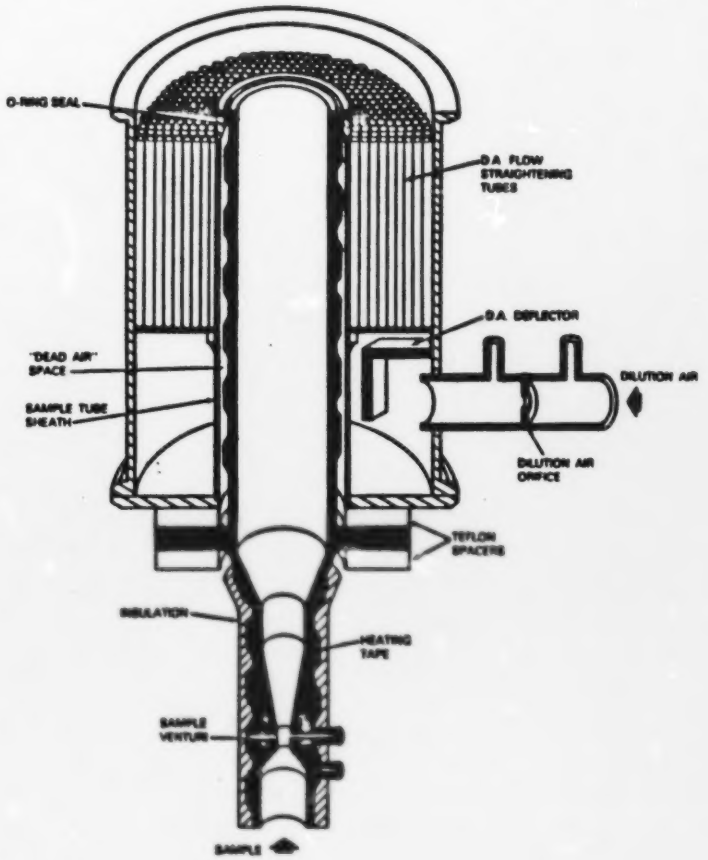

Figure 2. WSDSS sample inlet.

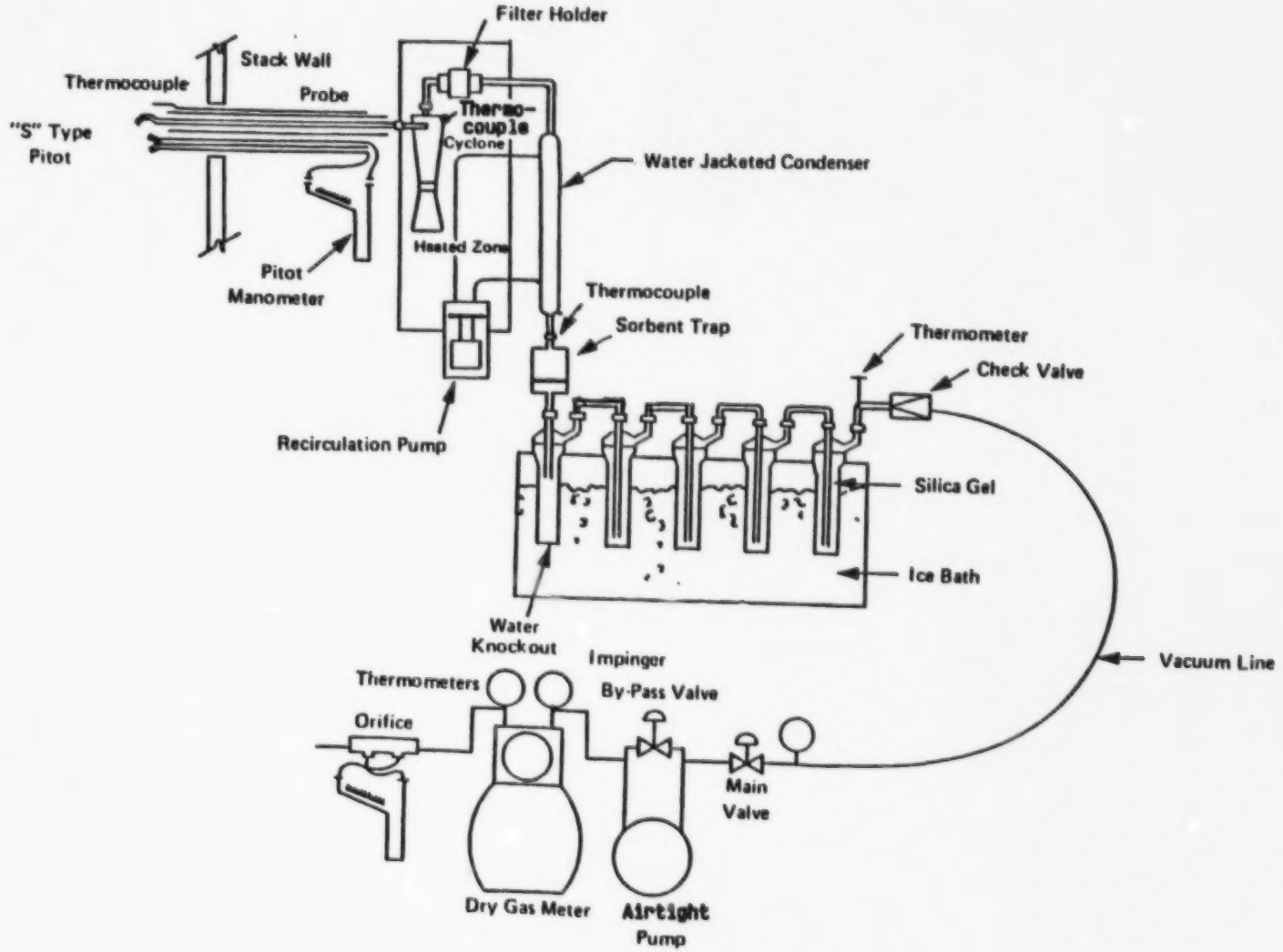

Figure 4. MM5 Train schematic diagram.

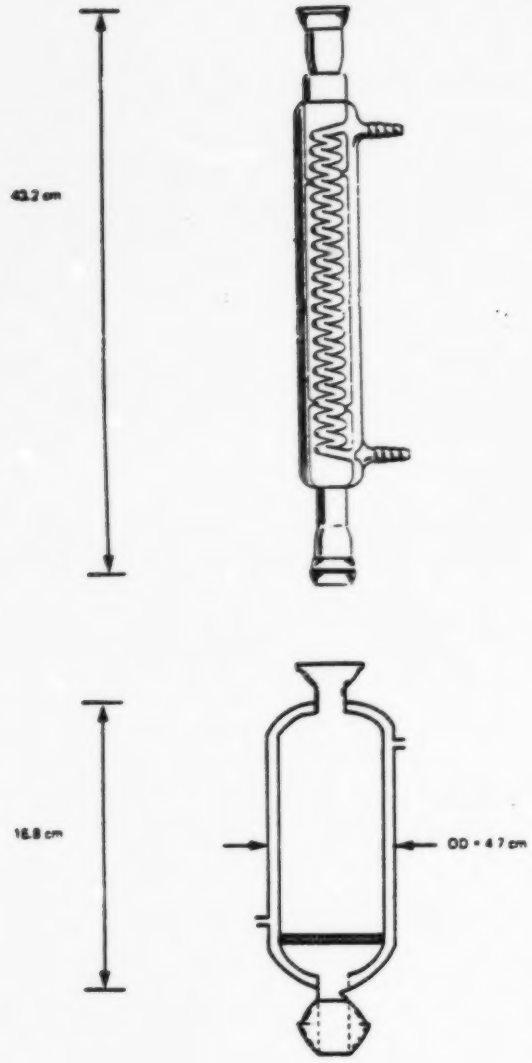

Figure 5. Acceptable sorbent module design No. 1.

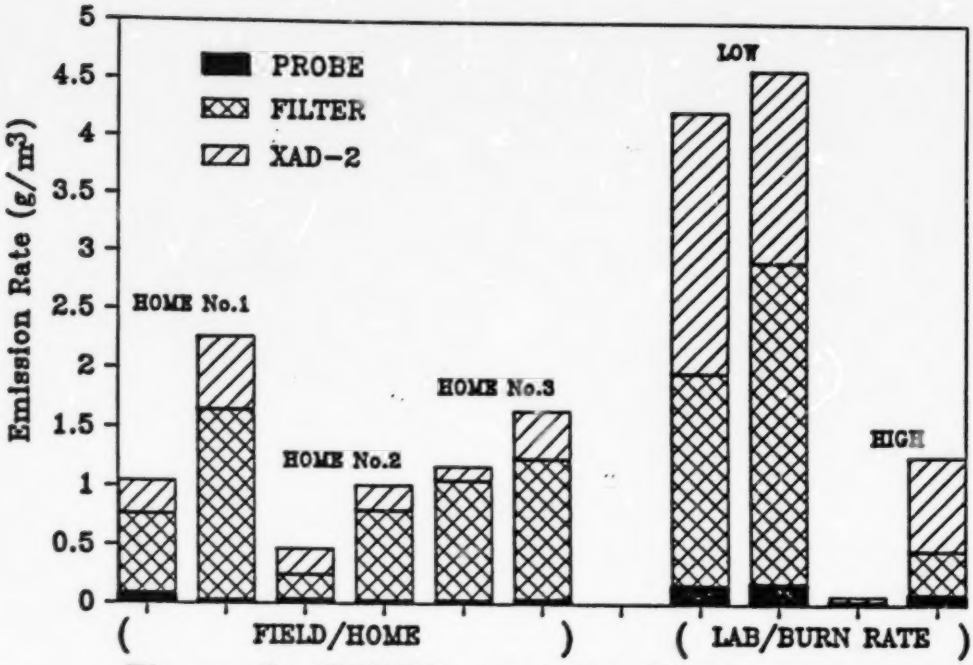

Figure 6. WSDSS mass distribution by sampler component (field and laboratory)